Natural experiment to measure change in energy use and indoor environment in dwellings with smart heat pump retrofits

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Abstract

The UK Government announced in 2020 its 'Ten Point Plan' for a green industrial revolution, which includes a challenging target to install 600,000 heat pumps per year by 2028. Balancing electricity supply and demand locally is key to the success of achieving this target. This paper uses a natural experiment approach to gather early insights into the change in energy use, indoor temperature and relative humidity profiles before and after installation of smart ground source heat pumps (GSHPs) and smart controls in nine social housing dwellings (5 bungalows, 4 flats) located in a socially-deprived area of Oxford (UK). The GSHPs replaced night-storage heaters and integrate smart controls to optimise heat production in line with outside weather and resident preferences. Indoor and outdoor temperature and relative humidity were continuously monitored at 15' intervals using blue-tooth enabled data loggers across the nine dwellings. In a subset of two dwellings, electricity use was monitored remotely using CT loggers from October to December 2020. Household surveys were conducted to establish the household characteristics, socio-demographics and the way residents heat their home. No correlation was observed between actual annual energy costs (self-reported) and EPC ratings. Indoor temperatures were found to be more stable across the nine dwellings after installation of heat pumps. Despite having similar size, number of occupants and occupancy patterns, there was wide variation in the range of indoor temperatures measured across the sample. Post-heat pump installation bungalows experienced higher increase in indoor temperature as compared to flats, with mean indoor temperatures of over 25 °C observed in mid-terraced bungalows, due to improved air-tightness as a result of cavity wall insulation, constant heating and limited window opening. Smart controls were found to be regularly used by residents to easily increase the heating set point temperature to overcome the low output temperatures of the heat pumps. Following heat pump installation, daily electricity use increased to 14.3 kWh/day (against 7.8 kWh/day) in the bungalows, and to 9.2 kWh/day (against 6 kWh/day) in the flats, however, when normalised for weather, daily electricity use was found to be reduced by 49 %. Electricity use for heating increased during the evening peak period, making a strong case for connecting to time-of-use tariffs to change the timing of electricity use so that heating is run in periods when electricity tariff is cheap and heating is avoided during the expensive peak periods.

Introduction

The UK government has committed to a net-zero emission target by 2050 (BEIS and Skidmore, 2019) with an interim target of 78 % reduction in carbon emissions by 2035 (CCC, 2020b) to address the growing concern of climate emergency by limiting the temperature rise to 1.5 °C (CCC, 2019a, CCC, 2019b). To meet the long-term carbon emissions reduction goals, UK energy system is going through rapid change by becoming decarbonised, decentralised and digitised (Ford et al., 2019, Foxon, 2013). Decarbonising heating in UK's domestic sector in line with the government 'Ten Point Plan'(HM Government, 2020) for a green industrial revolution sets out a challenging pathway to install 600,000 heat pumps every year by 2028 (BEIS., 2018). According to the Department for Business, Energy & Industrial Strategy (BEIS), about 19 million heat pumps have to be installed across the UK by 2050 to decarbonise heat (BEIS, 2021). This will be step-change the 20,000 heat pump units per year that are being deployed every year across the country (Carbon Trust, 2020). The Committee for Climate Change (CCC) in the most recent Six Carbon Budget has also emphasised the installation of 1 million heat pumps per year by 2030 as electricity generation becomes net zero by 2035 (CCC, 2020b, CCC, 2020a). Electrification of heating through heat pumps can also help to tackle fuel poverty given that around 10 % of households in England, 24 % in Scotland, 12 % in Wales and 18 % in Northern Ireland are classed as fuel poor (Bolton and Hinson, 2020). Having ability to control heating actively through smart controls can mitigate any rise in energy bills. However, the expected surge in heat pumps installation can exceed the capacity of the current UK electricity system with the peak load of around 60 GW (Watson et al., 2021), indicating the importance of shifting electricity demand and grid balancing to reduce pressure on the electricity network.

This paper used a natural experiment approach to examine the change in energy use, indoor temperature and relative humidity profiles before and after installation of smart ground source heat pumps (GSHPs) and smart controls in nine social housing dwellings (5 bungalows, 4 flats) located in a socially-deprived area of Oxford (UK). The GSHPs replaced night-storage heaters and integrate smart controls to optimise heat production and automatically load shift for grid stabilisation. Since the smart heating controls were not learning from residents' preferences and no residents signed up to the time-of-use (TOU) tariff, the study investigated the energy and environmental impacts of GSHPs in relation to night storage heaters. Indoor temperature and relative humidity were monitored before heat pump installation from 1st October 2020 to 8th October 2020, as well as after heat pump installation from 26th November 2020 to 15th December 2020, while electricity use was monitored in two dwellings. Household surveys were conducted to establish the household characteristics and heating patterns of residents receiving the heat pumps. Since due to Covid-19 pandemic nine out of 20 monitored dwellings received GHSPs by December 2020, this study has focused on these nine dwellings.

Literature review

While heat pumps require electricity to supply heating or hot water, they typically use less electricity to run than the heating that they produce thereby providing economic benefits. To get the maximum benefit from heat pumps, the first step is to improve energy efficiency of the building since it reduces heating demand (Rosenow and Lows, 2020). Two types of heat pumps are prevalent across the UK – ground source heat pumps (GSHP) that extract low-temperature solar energy stored in the ground or water using buried pipework and compress this energy into a higher temperature, and air source heat pumps (ASHP) that absorb energy from the air. Due to the lower capital cost and the cost and difficulty of installing ground infrastructure for GSHP, policymakers expect ASHPs to become more dominant in the UK (Howard and Crook, 2021). Since GSHPs deliver lower annual and daily peak electricity demand and provide opportunities to enhance efficiency through the use of waste heat, they are expected to acquire 40 % of the market with 1 GW to 7 GW reduction in peak electricity demand (Howard and Crook, 2021). This is vital since electrification of heating can increase the peak demand on local electricity networks and consequently require increased level of low carbon electricity generation to avoid expensive reinforcement of the network (Carbon Trust, 2020).

The Energy Saving Trust's (EST) domestic heat pump field trial in the UK was undertaken in two phases between 2008 and 2012 to examine the actual performance of heat pumps. Phase 1 of the trial with 53 installations showed poor system performance with annual Seasonal Performance Factor (SPF) values below 2.5 and users were not instructed on how to operate and control heat pumps efficiently (Bradford and Byrne, 2013). However, Phase 2 with 32 installations showed significant improvements in the installation, control and annual service checks of heat pumps leading to improved performance (Bradford and Byrne, 2013, Dunbabin et al., 2013). An evaluation of GSHPs in 83 dwellings in the UK showed that heat pump performance was affected by the thermal performance of the building fabric, which varied even in similar properties, indicating the need to upgrade building fabric alongside low carbon heating (Stafford and Bell, 2009).

A study conducted by Love et al. (2017) to assess the heat pump load profiles of 700 dwellings on the UK electricity demand showed an increase of 14 % to the peak load if 20 % of all buildings were fitted with heat pumps. To avoid such an increase, shifting the timing of heating is important for local grid balancing. Time-of-use (TOU) tariffs are designed to encourage users to shift energy use from the period with high energy rates to periods with cheap rates to reduce peak load (Rosenow and Lows, 2020). A study on adapting TOU tariff in 15 buildings in London found shifting the demand for heat outside of the peak time reduced energy cost by up to 23 % (Carbon Trust, 2020). Energy rates in TOU tariffs change by time of day, instead of charging users on a flat rate and regardless of time of use. The price signal can be either static, which is the same every day, and usually uses day and night pricing to reflect on peak and off-peak times broadly or can be dynamic that changes in response to real-time system conditions and charges on hourly rates (Hledik et al., 2017). Dynamic pricing schemes provide incentive to users to shift energy demand from the peak periods with high wholesale prices to lower priced hours giving opportunities to save energy cost, which can be change in a short notice (Wolak, 2010). To reduce network constraint, location-based tariff structures can be introduced to reflect costs associated with congestion in electrical networks and incentivise users to shift electricity use from the grid (BRIEF, 2019). The Octopus Agile tariff in the UK is an example of a dynamic pricing scheme offering half-hourly energy prices linked to the half-hourly wholesale market prices that updates on daily basis to reduce energy cost when whole sale price drops and daily electricity use is shifted outside peak hours (Octopus Energy, 2021). Users can be also alerted about times of plunge pricing that they can be paid to take excess energy from the grid and reduce pressure (Kensa, 2020). To use the tariff, it is essential to have smart meters for half-hourly consumption measurements.

Shifting the timing of heating demand in response to price signals or when abundant low carbon electricity supply is available can enable heat pumps to provide Demand Side Response (DSR) services. This process can be automated through smart heating controls. Smart controls deliver efficiency through automation, zoning and integration of multiple technologies allowing optimised operation by automatically responding to price signals. Smart heating controls that can be also managed through mobile apps allow for heating automation through algorithms that can set heat generation timings based on indoor and outdoor temperature, occupancy patterns and resident preferences, as well as the characteristics of the heat generators aiming to improve thermal comfort and reduce energy use (Carmichael et al., 2020) and when combined with TOU tariffs it can help to shift electricity load from the peak hours and reduce network constraint. The recently-completed Freedom Project undertaken in the UK installed 75 smart hybrid heating systems combining conventional gas boilers with ASHPs and smart controls demonstrated that running costs of the heat pumps can be reduced through load shifting, while guaranteeing heating during peak winter period (Freedom, 2018). Recently completed trials of smart control technology for coordinating heat pumps with smart heating control with electric vehicles, solar PV panels and domestic battery revealed energy cost savings of £260 per year and local network saving of £310 with peak load shifting between 35 % and 40 % (Calder, 2020). Residents benefitted from the TOU tariff by shifting demand outside of peak times (Howard and Crook, 2021). The users' preferences and heating schedule can be also aligned to time of low carbon and low-cost electricity when GSHPs are integrated with smart control that synchronise hourly energy rates published by dynamic pricing tariffs (Kensa, 2020). If the building's fabric is also insulated along with heat pump installation and smart controls, it can potentially lead to energy demand reduction and demand side response (Carmichael et al., 2020). This study seeks to empirically examine the electricity use and indoor environmental conditions in dwellings with GSHP retrofits and smart heating controls to see what works and for whom.

Methodology and case studies

The study used a mixed methods approach drawing from building science and social science as follows:

- Household survey to identify household characteristics, socio-demographics and ways residents heat homes
- Identifying physical characteristics of dwellings using Energy Performance Certificates (EPCs).
- Monitoring of indoor temperature and relative humidity (RH) at 15-minute intervals in nine dwellings from October 2020 to December 2020 covering the period of before and after heat pump installation.
- Monitoring of electricity use at 15-minute intervals in two dwellings from October 2020 to December 2020.

HOUSEHOLD SURVEY

Household survey was designed to find out how residents used their heating and electricity before heat pump installation. This involved asking questions about the current heating system, electricity use, and the number of people in the household. The interview-based survey was conducted in person with social distancing protocols in place from August 2020 to September 2020 before heat pumps were installed. To avoid sharing paper, the survey was implemented using Google forms accessible through the smart phone. The key survey variables are presented in Table 1, and consisted of questions on socio-demographics (gender, age, employment, occupancy and annual income), type of heating system, heating regime, energy cost and affordability. To understand the timing of energy use, residents indicated their current usage of electrical equipment and potential to load shift outside the peak period (4 pm to 7 pm). The questions included scalar (e.g., age, energy cost and income), nominal (e.g., economic and employment status) and ordinal variables (e.g., agreement regarding electricity and heating use) using Likert scale from 1 (strongly disagree) to 5 (strongly agree).

PHYSICAL MONITORING

Physical monitoring of indoor temperature and relative humidity (RH) was undertaken using blue-tooth enabled HOBO MX1101 loggers. They were wall-mounted in the living rooms of the nine dwellings and covered periods from 1st Oct 2020 to 8th Oct 2020 (before heat pump) and from 26th November 2020 to 15th December 2020 (after heat pump). Outdoor temperature and RH were also measured using HOBO MX2301. Electricity use for heating system and electrical appliances was monitored in two dwellings using Loop device, which was connected to the electricity meter of each dwelling covering the pre and post heat pump installation periods. Tables 2 and 3 show specifications of environmental monitoring devices and heat pump installation dates across the nine dwellings including five bungalows (C01, C02, C03, C04 and C05) and four flats (B01, B03, B04 and B05) respectively.

PHYSICAL AND OCCUPANCY CHARACTERISTICS OF CASE STUDY DWELLINGS

The nine social housing dwellings consisted of five bungalows and four flats located in an estate within a socially-deprived area in Oxford (UK). GSHPs and smart controls were in-

Table 1. Survey variables for households, heating and electricity.

Household variables	Heating	Electricity
Number of occupants	Type of heating control	Type of meter
Occupancy pattern	Heating use frequency	Type of energy tariff
Age	Heating set point temperature	Energy cost
Ethnicity	Number of months heating is on	Energy bill payment type
Income group, employment status	Understanding of heating controls	Bill payment frequency

Table 2. Specification of monitoring device to measure temperature and relative humidity.

Device	Parameter	Range	Accuracy
HOBO MX1101 (36.6 x 84.8 x 22.9 mm)	Indoor temperature (°C)	-20–70	±0.2
	Indoor relative humidity (%)	1–90	±2 (20 % to 80 %), ±6 (below 20 % and above 80 %)
HOBO MX2301 (108 x20 x 8.8 mm)	Outdoor temperature (°C)	-40–70	±0.2
	Outdoor relative humidity (%)	0–100	±2.5–3.5 (10 % to 90 %), ±5 (below 10 % and above 90 ß%)

Table 3. Heat pump installation dates and monitoring periods before and after heat pump installation.

Dwellings		Heat pump installation	Monitored data	Monitoring Period	
				Before	After
Bungalow	C01	9 Oct 2020	Temp (°C), RH (%) and electricity use (kWh)	1 Oct 2020– 8 Oct 2020	26 Nov 2020– 15 Dec 2020
	C02	21 Oct 2020	Temp (°C) and RH (%)		
	C03	29 Oct 2020	Temp (°C) and RH (%)		
	C04	05 Nov 2020	Temp (°C) and RH (%)		
	C05	14 Oct 2020	Temp (°C) and RH (%)		
Flat	B01	25 Nov 2020	Temp (°C) and RH (%)		
	B03	23 Nov 2020	Temp (°C) and RH (%)		
	B04	19 Nov 2020	Temp (°C), RH (%) and electricity use (kWh)		
	B05	12 Nov 2020	Temp (°C) and RH (%)		

Table 4. Dwelling characteristics before heat pump installation extracted from EPC certificates.

Dwellings characteristic	Bungalow					Flat			
	C01	C02	C03	C04	C05	B01	B04	B03	B05
Type	Mid-terraced	End-terraced	Mid-terraced	End-terraced	Mid-terraced	Ground floor	Ground floor	Top floor	Top floor
Energy efficiency rating	D	E	D	D	D	C	C	C	C
Environmental impact rating	E	F	E	E	E	D	D	D	D
Dwelling floor area (m²)	60	47	47	47	60	33	33	33	33
Predicted heating demand (kWh/y)	6,346	7,600	5,237	5,264	6,346	2,318	1,722	2,302	2,507
Predicted energy use (kWh/m²y)	428	612	461	460	428	365	310	367	382
Roof insulation	270 mm loft insulation					N/A		270 mm loft insulation	
Building fabric insulation	Filled cavity wall								
Glazing	Double glazed								
Main heating	Night storage electric heating								

stalled in these dwellings along with filled cavity wall insulation. Although smart controls allow users to control heating set point temperature and duration, the self-learning capability of the controls was not implemented in the study. The physical characteristics of the dwellings were obtained from Energy Performance Certificates (EPCs) as summarised in Table 4. All nine dwelling had double glazed windows and the main heating system before heat pump installation was night-storage electric heaters. While flats (B01, B03, B04 and B05) had energy rating of C, bungalows (C01to C05) had energy rating of D or E, implying potential for further improvement. The heating demand of bungalows pre-heat pump installation was higher than flats, ranging from 5,237 kWh/year to 7,600 kWh/year, as compared to flats that ranged from 1,722 kWh/year to 2,507 kWh/year.

Results

HOUSEHOLD CHARACTERISTICS AND HEATING PREFERENCES BEFORE HEAT PUMP INSTALLATION

Household characteristics including number of occupants, age group, employment status and income group, as well as annual energy cost (self-reported by residents) before heat pump installation are presented in Table 5. Although all dwellings had single occupancy and average annual income was less than £15,000 (€17,667), no significant relationship was identified between income and annual energy cost. While bungalows were largely occupied by elderly residents (aged 65 years and above), flats were occupied by younger residents.

The distribution of annual energy costs (self-reported by residents) and annual heating energy demand (left), as well as total floor area (right) before heat pump installation across eight dwellings is presented in Figure 1. Bungalow C02 refused to provide total energy cost of their home and is therefore excluded from this analysis. Despite EPCs predicting higher heating demand for bungalows due to higher exposed area, the self-reported annual energy cost of bungalows around £600 was much lower than the annual energy cost figure of £800 in flats. Moreover, it was evident that energy costs across the eight dwellings had no relationship with predicted heating demand (EPC) or area of dwellings, although all the case study dwellings were located in the same estate and had a single resident each. This variation was more evident across the sample of four flats, wherein energy cost ranged from £480 to £1,080 despite having the same internal floor area and single occupancy.

The bungalows and flats had slightly different occupancy patterns (Figure 2). While all five bungalows and three flats were occupied either *most of the time* or *continuously*, one flat was occupied *during the weekends*. Despite similar occupancy patterns across the nine dwellings, the wide variation in energy costs confirmed that there was no association between occupancy pattern and energy use.

Most of the residents admitted that the night storage heating system was expensive to run. While residents in bungalows understood how the night storage heaters worked with average rating of 4.5 (scale of 1–5), residents in flats had low level of understanding with average rating of 2.5, indicating why they had a higher energy cost. While majority of residents in bungalows preferred to wear warm clothes to reduce heating energy use, this was not the case in flats possibly due to the difference in

Table 5. Household characteristics in bungalows and flats.

Household characteristics	Bungalow					Flat			
	C01	C02	C03	C04	C05	B01	B03	B04	B05
No of occupants	1	1	1	1	1	1	1	1	1
Age of residents (years)	54	78	66	60	86	63	54	67	50
Employment status	Employed	Retired	Retired	Employed	Retired	Retired	Employed	Retired	Employed
Income group	<£15 K	<£15 K	<£15 K	<£15 K	£15–29.9 K	<£15 K	£15–29.9 K	<£15 K	<£15 K
Annual energy cost (£)	£1,080	No data	£380	£520	£364	£780	£480	£1,080	£1,000

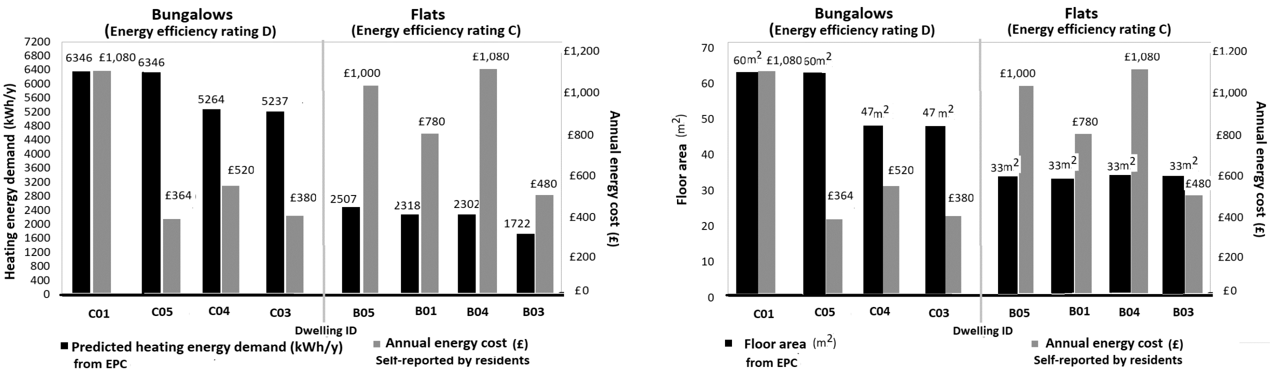


Figure 1. Bar charts showing the distribution of heating energy demand (kwh/y) and annual energy cost (left), as well as floor area (m^2) and annual energy cost (right) in relation to energy efficiency rating band.

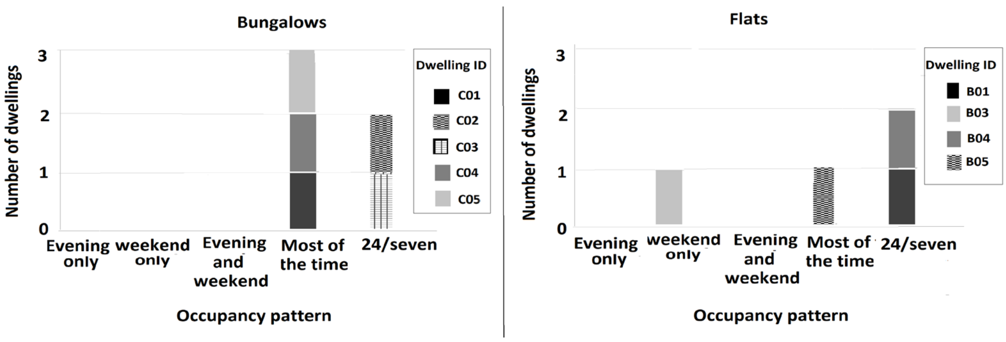


Figure 2. Occupancy patterns in bungalows (left) and flats (right).

age groups of the residents. Although majority of residents in bungalows and flats admitted they would be willing to change the timing of energy use to save energy cost, there was a lack of interest in changing the energy supplier to move to a TOU tariff, reflecting the difference between 'saying' and 'doing'.

INDOOR TEMPERATURE AND RELATIVE HUMIDITY BEFORE AND AFTER HEAT PUMP INSTALLATION

Descriptive statistics were produced to identify changes in indoor temperature before and after heat pump installation across the nine dwellings (Table 6). The mean indoor temperature after heat pump installation increased to 21.2 °C–25.6 °C across the five bungalows, higher than 18.9 °C–22.8 °C measured before heat pumps. This may be due to the installation of cavity wall insulation in the bungalows following the installation of heat pumps. On the other hand, there was not a major change in mean indoor temperatures after heat pump installation across the four flats. In fact, in flat B04, mean indoor temperatures reduced from 24 °C to 21.7 °C after heat pump installation since the residents preferred to keep the windows open when the heating was on. Although indoor temperatures did not go below 17 °C across the nine dwelling, there was wide variation observed in indoor temperatures measured across the five bungalows, ranging from 18 °C to 28.8 °C.

As shown in Table 6 above and Figure 3 below, bungalows experienced higher increase in indoor temperature after heat pump installation as compared to flats. The mean indoor temperature in bungalows increased to 23.4 °C (from 20.4 °C) post heat pump installation, while there was a slight decrease in mean indoor temperature in flats from 22.6 °C to 22.1 °C post heat pump installation. Across the five bungalows, a wide range in indoor temperature from 18 °C to 28.8 °C (Figure 3) was observed after heat pump installation indicating the variation in heating preferences of residents. The range in indoor temperature was narrower across the four flats (17.6 °C to 26 °C). The mean indoor temperature was found to be highest in mid-terraced bungalows (C03 and C05) to > 25 °C after heat pump installation, as compared to 21.2 °C and 22 °C in end-terraced bungalows (C02 and C04), possibly due to their larger exposed area.

The distribution of monitored indoor and outdoor temperatures before and after heat pump installation in each of the nine dwellings is shown in Figure 4. As evident, all nine dwellings experienced more stable indoor temperatures (with lower peaks) after heat pump installation with a wide variation in indoor temperatures across the sample. Figure 4 reaffirmed that apart from flat B04, indoor temperatures in the other three flats did not change much after heat pump installation. On the other hand, bungalows C03 and C05 experienced high indoor temperatures and for longer duration as compared to other three bungalows. Despite the move to low carbon form of heating, weak correlation (-0.1 to 0.3) was observed between indoor and

Table 6. Descriptive statistics on indoor temperature in bungalows and flats before and after heat pump.

Bungalow	Timeline	Indoor temperature °C					Flat	Timeline	Indoor temperature °C				
		N	Min	Max	Mean	Std. Deviation			N	Min	Max	Mean	Std. Deviation
C01	Before	768	18	22	18.9	0.8	B01	Before	768	22.5	25.0	24.1	0.4
	After	1,920	21	26	23.1	1.0		After	1,920	19.6	26.0	24.0	1.0
C02	Before	768	18	21	19.2	0.8	B03	Before	768	19.0	27.8	21.4	1.5
	After	1,920	18	28	21.2	1.5		After	1,920	18.3	24.8	21.6	1.3
C03	Before	768	21	25	22.8	0.9	B04	Before	768	20.3	25.3	24.0	0.9
	After	1,920	22	28.8	25.6	1.3		After	1,920	19.0	24.1	21.7	1.0
C04	Before	768	18	24	19.5	1.0	B05	Before	768	18.1	25.1	21.0	1.9
	After	1,920	19	25	22.0	1.2		After	1,920	17.6	24.4	21.0	1.4
C05	Before	768	20	25	21.6	0.7							
	After	1,920	21	28	25.0	1.4							

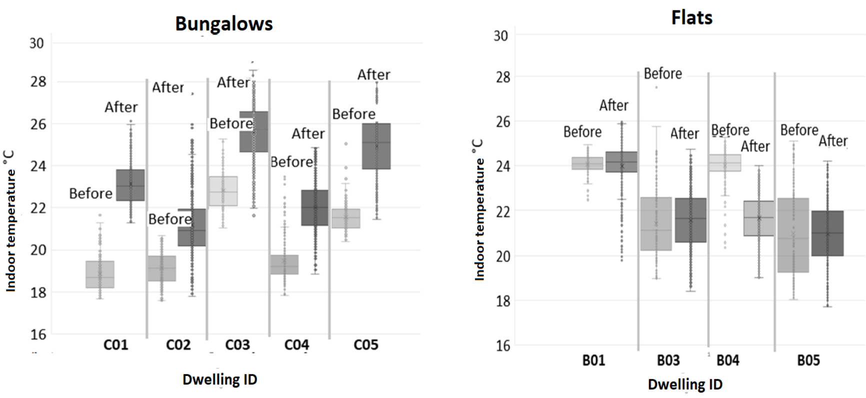


Figure 3. Distribution of indoor temperature in bungalows (left) and flats (right) before-after heat pump.

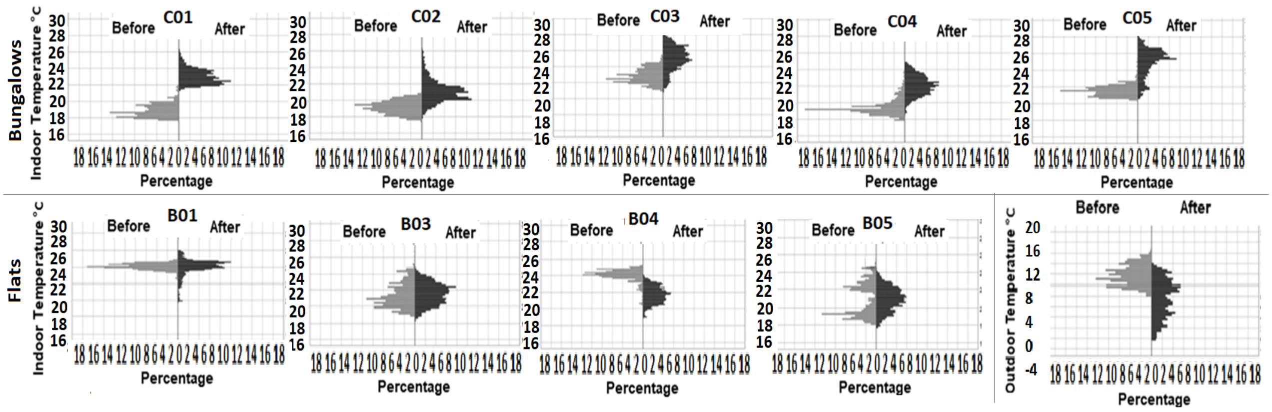


Figure 4. Distribution of indoor temperature in bungalows (top) and flats (down) before and after heat pump.

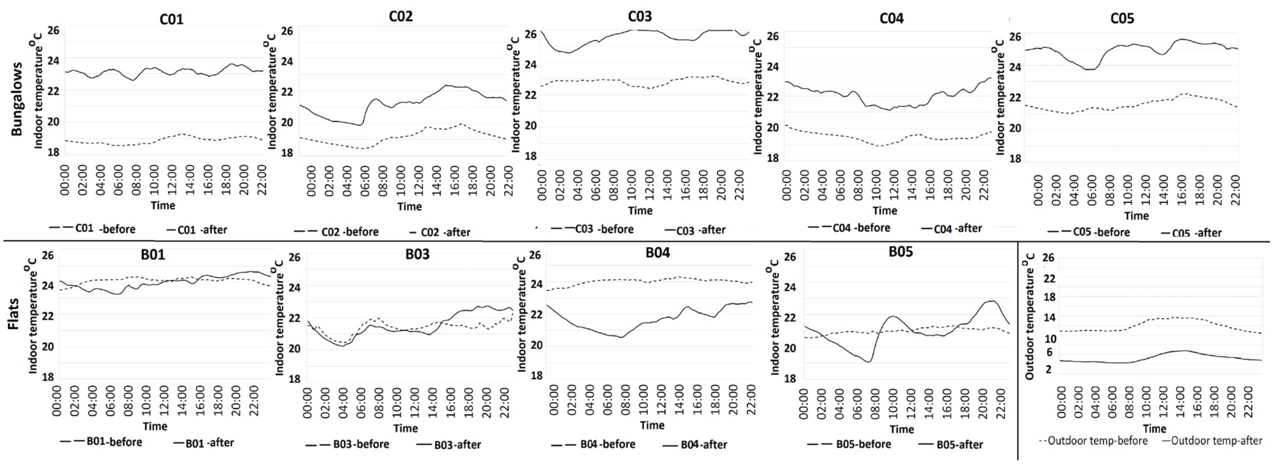


Figure 5. Daily mean temperature profiles in bungalows (top) and flats (down) before and after heat pump.

outdoor temperature indicating the need to manage heating in relation to outdoor weather, which could also bring down the high indoor temperatures.

Daily mean temperature profiles (using 15-minute data) before and after heat pump installation for bungalows and flats are presented in Figure 5. As shown in the descriptive statistics, despite having the same heating system with similar dwelling size and occupancy pattern, there was a wide variation in the daily temperature profiles across the nine dwellings due to heating preferences of residents. Although the magnitude of indoor temperatures was higher post heat pump installation, the occurrence of peaks and troughs did not change, indicating that residents continued to use the heat pumps in a similar way to night storage heating. Although there was increase in indoor temperature from 6:00 am to 10:00 pm in majority of dwellings post heat pump installation, temperatures peaked between 4:00 pm and 7:00 pm, indicating that electrical energy used by heat pumps was adding to the evening peak period of electricity demand in the UK. The smart heating controls of the heat pumps could be used to run heating before or after the peak period.

To reveal the cause for variation in indoor temperatures across the sample of nine dwellings, the distribution of indoor temperature before and after heat pump installation for each dwelling was analysed by socio-demographic factors including resident age band, employment status and annual income. As shown in Figure 6, bungalows with elderly residents (65 years and above) were found to experience higher indoor temperature after heat pump installation possibly because older people are sensitive to cold and prefer to have higher indoor temperatures. In two mid-terraced bungalows C03 and C05, indoor temperature reached >28 °C due to increase in heating set point temperature since residents presumed that heat would be retained due to insulation and low carbon heating, indicating prevalence of rebound effect. Instead of letting heating run constantly at low temperature to maximise the efficiency of the heat pumps, these residents admitted to turning heating on/off frequently. It is clear that low carbon heating with smart controls may not be enough; residents need to be trained to use low temperature output heating to maximise comfort and minimise heating cost.

In contrast to indoor temperature, indoor RH range in bungalows was found to be similar to flats before heat pump installation, ranging from extremely low to extremely high (30 % to over 80 %). However, indoor RH was significantly reduced in bungalows after heat pump installation possibly due to more continuous heating as indicated by higher indoor temperatures (Figure 7), while the change was much subtle in the flats in line with the minimal change in indoor temperature after heat pump installation.

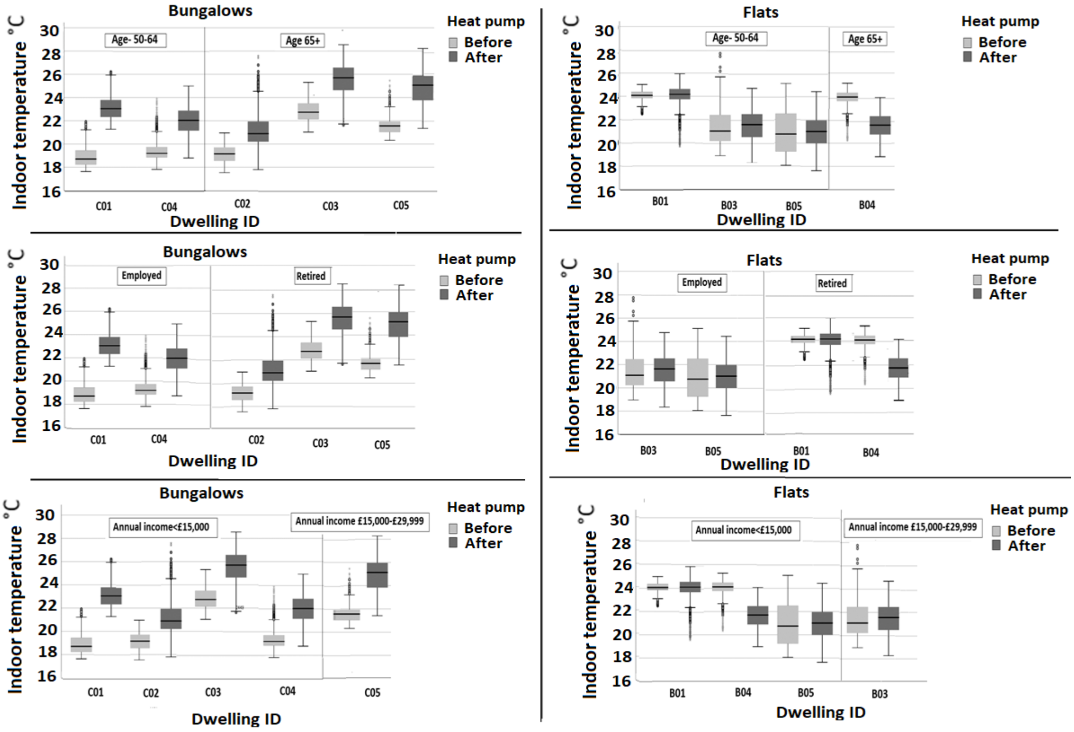


Figure 6. Distribution of indoor temperature in each bungalow and flat before and after heat pump installation based on residents' age band (top), employment status (middle) and annual income (down).

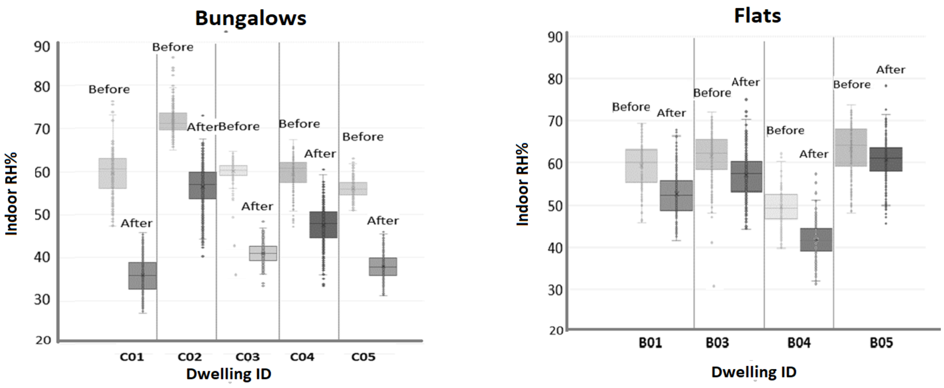


Figure 7. Boxplot showing distribution of indoor RH in bungalows (left) and flats (right) before and after heat pump.

After heat pump installation, the correlation between indoor temperature and indoor RH was found to be (negatively) moderate in three out of the five bungalows probably due to continuous heating and insulation (Table 7), while no significant correlation was observed between indoor temperature and indoor RH across the flats.

ELECTRICITY USE IN TWO DWELLINGS

Descriptive statistics were produced for electricity use in bungalow C01 and flat B04 alongside daily electricity use, as presented in Figure 8. Daily electricity use (kWh) was found to be higher after heat pump installation in both dwellings, due to colder weather (lower ambient temperatures) and heating being constantly on. Daily electricity use was 7.8 kWh in C01 compared to 14.3 kWh after installation of heat pump. Despite an increase in electricity use in B04 after heat pump installation, daily electricity use (kWh) was lower than C01 averaging 6.0 kWh before heat pump installation, as compared to 9.2 kWh after installation. Although daily electricity use increased in C01and B04 after heat pump installation, mean indoor temperature reduced slightly in B04 possibly due to residents keeping windows open (as observed during home visits).

To account for weather, electricity use before and after heat pump installation was normalised for outdoor temperature. This was necessary since the post-heat pump period fell in the colder months (November – December 2020) and increase in heating energy use was expected. Regression analysis was conducted between outdoor temperature, electricity use and Heating Degree days (HDD) using a base temperature of 15.5 °C (Table 8) to normalise daily electricity use in each dwelling by the corresponding HDD. Results presented in Figure 9 showed lower electricity consumption per HDD after heat pump installation despite colder outdoor temperature. Electricity use reduced from 2.2 kWh/HDD to 1.34 kWh/HDD in C01, and from 1.70 kWh/HDD to 0.86 kWh/HDD in B04 after heat pump installation showing the energy benefit of using heat pump. When electricity use was correlated with outdoor temperature, there was moderate correlation before/after heat pump installation in C01 (R=0.5), while the correlation reduced in B04 (from 0.4 to 0.2) possibly due to residents keeping windows open.

Daily electricity use profiles of the two dwellings (Figure 10) showed different patterns of electricity use before and after heat pump installation. Before heat pump installation, electricity use across the two dwellings peaked overnight since the heating system was night-time storage heaters. In C01 electricity use peaked between 11:00 pm and 12:00 am rising to above 0.5 kWh, while in B04 it peaked between 12:00 am and 1:00 am reaching over 0.7 kWh. In contrast after heat pump installation, the magnitude of the peak in electricity use was lower and distributed across the day since the heat pump was left mostly on. Daily electricity use peaked around 6:00 am, 2:00 pm and 6:00 pm in B04 and around 4:00 am, 9:00 am and 7:00 pm in C01. The timing of evening peak fell in the national evening peak period of electricity use.

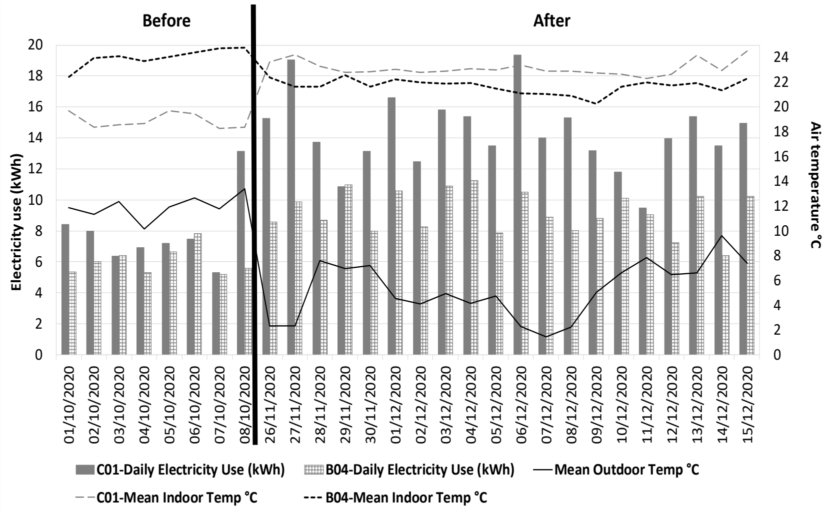
The daily electricity use before and after heat pump installation (Figure 11) was found to be higher in mid-terraced bungalow (C01) than the ground floor flat (B04) before and after heat pump installation since C01 had larger floor area (60 m²) and lower EPC rating as compared to flat B04 which was half in size (33 m²). The scatter plot of mean indoor temperature against daily electricity use (kWh) in C01 and B04 (Figure 11) showed no correlation between daily mean indoor temperature and daily electricity use in C01(R=-0.1) and B04 (R=0.3) before heat pump installation. However moderate correlation was observed between the two in C01 (R=0.6) and B04 (R=0.4) after heat pump installation.

Discussion

The study gathered household data through surveys along with time-series (monitoring) data on indoor temperature, indoor RH and electricity use before and after installation of GSHPs in five bungalows and four flats' dwellings during the heating

Table 7. Pearson's correlation between indoor temperature and indoor RH in flats and bungalows.

Pearson's correlation between indoor temp and indoor RH	Timing	C01	C02	C03	C04	C05	B01	B03	B04	B05
	Before	-.31**	-.26**	-.37**	-.61**	-.27**	-.52**	-.70**	-.40**	-.49**
	After	-.43**	**-.61****	**-.53****	-.39**	**-.48****	-.06**	-.25**	-.06*	-.34**
**Correlation significant at 0.01 level (2-tailed), *Correlation significant at 0.05 level (2-tailed).										



Dwelling	Timeline	Daily electricity use (kWh)				
		N	Min	Max	Mean	Std. Deviation
C01	Before	8	5.3	13.1	7.8	2.4
	After	20	9.5	19.4	14.3	2.3
B04	Before	8	5.2	7.8	6.0	0.9
	After	20	6.4	11.3	9.2	1.4

Figure 8. Daily electricity use (kWh) and daily average indoor and outdoor temperature profiles in C01 and B04 before and after heat pump installation (left), and descriptive statistics analysis for daily electricity use (right).

Table 8. Pre- and post-heat pump installation electricity use normalised for weather.

Dwelling	Timing	Mean outdoor temperature (°C)	Total HDD	Total electricity use (kWh)	Electricity use (kWh)/HDD	Electricity use (kWh)/HDD/day
C01	Before	11.9	3.5	62.8	2.20	0.28
	After	5.2	213.5	286.6	1.34	0.07
B04	Before	11.9	3.5	48.3	1.70	0.21
	After	5.2	213.5	184.4	0.86	0.04

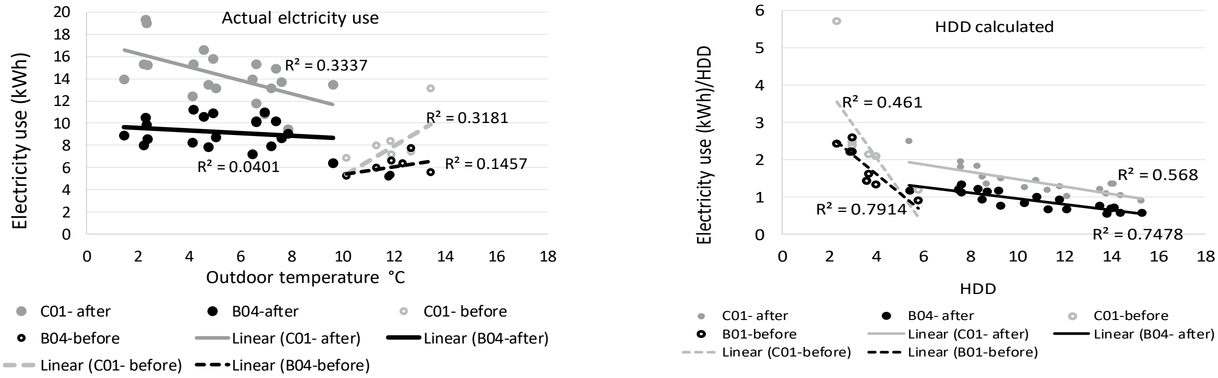


Figure 9. Correlation between total electricity use (kWh) and mean outdoor temperature (left) and normalized electricity use (kWh)/HDD and HDD (right).

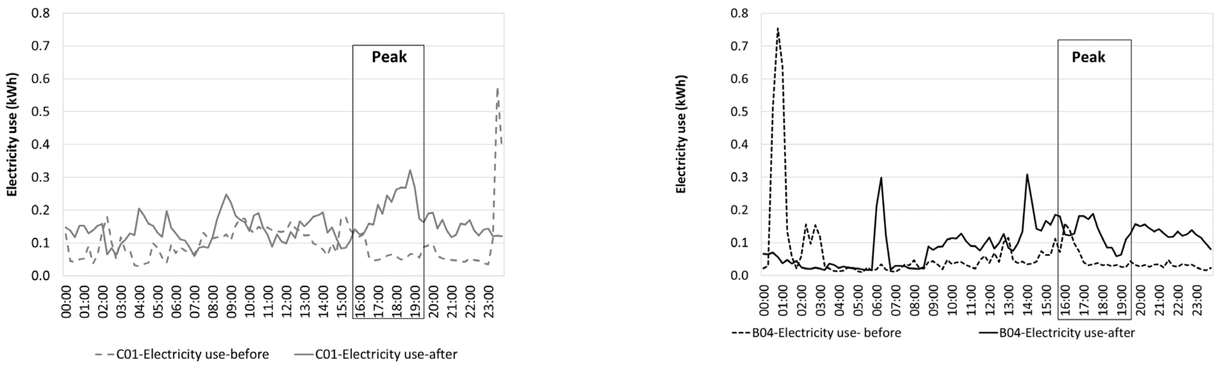


Figure 10. Daily average electricity use profiles in C01(left) and B04 (right) before and after heat pump.

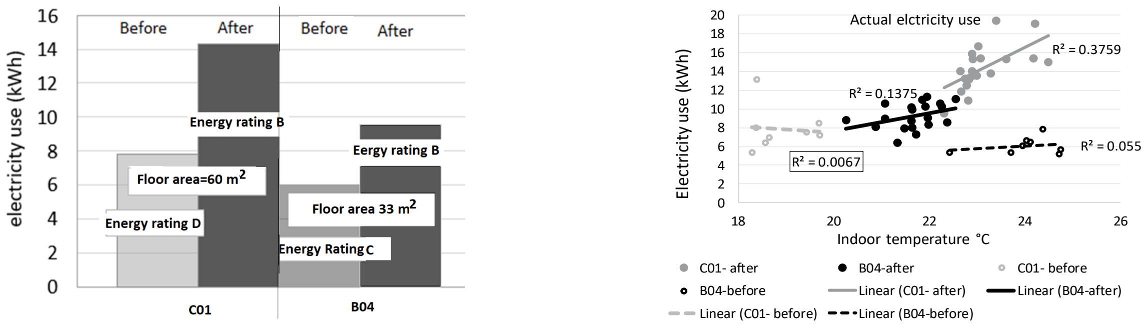


Figure 11: Daily average electricity use (kWh) in C01 and B04 before and after heat pump installation in relation to type of dwelling, energy rating and floor area (left), and scatter plot of mean indoor temperature and daily electricity use (kWh) in C01 and B04 before and after heat pump installation (right).

season from October 2020 to December 2020. Despite a small sample size, interesting findings have emerged. Surprisingly there was no correlation observed between the energy efficiency rating (EPC) of the dwelling (or predicted heating energy demand) and annual energy cost, reinforcing the fact that resident behaviour has a significant influence on energy costs. This has implications for the current practice of local authorities and energy companies to use EPC data to target suitable dwellings (with low EPCs) for low carbon heating since dwellings with high energy costs may not necessarily have a low EPC rating. It is recommended that household surveys that gather data on household characteristics including energy costs should be encouraged when data for EPC ratings are gathered.

Although post heat pump installation, indoor temperatures were found to be warmer and more stable across the dwellings, bungalows experienced excessively high indoor temperatures (of 25 °C and above) due to a combination of factors, that included improved air-tightness as a result of wall insulation along with heating being constantly on, and limited window opening. Moreover, smart controls which were designed to learn from resident behaviour, were used in unintended ways by residents, for instance to easily increase the heating set point temperature to overcome the low output temperatures of the heat pumps. This reinforces the need to train residents to understand the benefit of *constantly-on* low temperature heating in providing comfort as against *on-demand* heating. Also, underfloor heating can be deployed with heat pumps that provides a 'wider' area of heating than the radiators. This may increase overall costs of installing heat pumps.

The electricity use was monitored in two out of nine dwellings since the electricity monitoring device required broadband internet connection to transfer monitoring data remotely to the cloud. Unexpectedly it was found that not all case study dwellings had a broadband connection. In future it is vital that smart energy monitoring solutions for social housing dwellings do not assume widespread prevalence of broadband. Instead, transmission of monitoring data is addressed using other means of communication such as GSM card. Most of the dwellings were found to be on pre-payment meters which made it challenging to gather historical data as baseline electricity use. Weekly and daily meter readings provided a useful alternative in the absence of smart meters.

Better management of heating through smart controls was evident through the moderately strong correlation that was observed between indoor temperature and electricity use. This relationship was absent before the installation of heat pumps. The analysis of normalised electricity use per heating degree day (kWh/HDD) in the two dwellings showed nearly 49 % reduction in electricity use after heat pump installation despite colder weather in November–December and the heat pumps being constantly on, reaffirming the efficient running of the heat pumps that utilised a fraction of electricity to produce heat. Further energy savings may become apparent as the self-learning capability of the smart heating control from the residents' behaviour gets implemented.

The indoor temperature profiles of the nine dwellings and electricity profiles confirmed the rise in indoor temperatures (and electricity use) during the evening peak periods. Although the peaks in electricity use of the two dwellings were lower (than night storage heating) and more distributed during the daytime, utilisation of available renewable electricity locally may become necessary to enable local grid balancing and avoid local network issues due to increase in electrical heating demand. The evening peaks in electricity use observed in the two monitored dwellings reinforces the need to integrate TOU tariff which can encourage load shifting. Heating can be run in periods when electricity rate is cheap and rise in electricity bills is avoided especially for the social housing dwellings. Smart heating controls can automate this process by optimising the running of the heat pumps based on indoor and outdoor temperature, occupancy patterns, resident preferences and price signals.

Conclusion

This paper used a natural experiment approach to provide early insights into changes in energy use, indoor temperature and relative humidity profiles before and after installation of GSHPs in nine social housing dwellings (5 bungalows, 4 flats) located in a socially-deprived area of Oxford. The GSHPs replaced night-storage heaters and integrated smart controls. Household surveys provided contextual data on household characteristics, socio-demographics and heating preferences, while physical monitoring generated time-series data on indoor temperature, RH and electricity use before and after installation of GSHPs. The data was gathered during the heating season from October 2020 to December 2020.

Indoor temperatures were found to be more stable across the sample of five bungalows and four flats after installation of heat pumps. Despite having similar size, number of occupants and occupancy patterns, there was a wide variation in the range of indoor temperatures measured across the sample. No correlation was observed between annual energy costs and EPC ratings raising concerns about purpose of EPCs. Bungalows experienced excessively high indoor temperatures (of 25 °C and above) and low RH due to improved air-tightness as a result of wall insulation, heating left on and limited window opening. Smart controls were found to be regularly used by residents to easily increase the heating set point temperature to overcome the low output temperatures of the heat pumps.

Following heat pump installation, daily electricity use increased to 14.3 kWh/day in the bungalows and 9.2 kWh/day in the flats, however, when normalised for weather, electricity use was reduced by 49 %. Electricity use for heating increased during the evening peak period making a strong case for connecting such dwellings to TOU tariffs with different prices in the peak and off-peak periods in line with whole-sale prices. This could lead to demand side response (changes to the time of electricity use) and local grid balancing, enabled by smart controls. Since such automated control systems will inherently introduce more complexity in homes with heat pumps, it is vital to strengthen engagement with residents and improve their knowledge and understanding on low carbon heating and TOU tariffs. This will require efforts by housing associations, local authorities and national government.

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